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Extant and Extinct Lunar Regolith Simulants: Modal Analyses of NU-LHT-1M and -2m, OB-1, JSC-1, JSC-1A and -1AF, FJS-1, and MLS-1

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Participants

NASA - Marshall Space Flight Center leads this simulant development and characterization

JSC, GRC, and KSC contribute other work towards the characterization of simulant and lunar materials

The United States Geological Survey in Denver assists in characterization and leads in the manufacturing of NU-LHT series

Intellection, Ltd., in Brisbane and Intellection Corp., USA in Westminster CO

Purpose

- This work is part of a larger effort to compile an internally consistent database on lunar regolith (Apollo samples) and lunar regolith simulants.
  - Characterize existing lunar regolith and simulants in terms of
    - Particle type
    - Particle size distribution
    - Particle shape distribution
    - Bulk density
    - Other compositional characteristics
  - Evaluate regolith simulants (Figure of Merit) by above properties by comparison to lunar regolith (Apollo sample)

This presentation covers new data on lunar simulants.

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User's handbook

The NASA-MSFC simulant group is compiling a simulant user's handbook with a matrix of simulant properties.

This will help guide users choose a simulant for their applications.

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Outline

1) Simulant types and specific simulants

1) New work – modal data
   A. QEMSCAN® instrument and approach
   B. Preliminary results of modal analysis of simulants
      i. Plagioclase
      ii. Pyroxene
      iii. Olivine
      iv. Glass

2) Phase chemistry (mostly previous work)
   A. Plagioclase composition
   B. Glass composition

3) Examples of other new results

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Lunar simulants -- mare and highlands

JSC-1A lunar mare simulant

NU-LHT-1M lunar highlands simulant

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Current emphasis

NASA lunar architecture places the first permanent bases near a pole, which is likely dominated by lunar highlands-type terrain.

NASA-MSFC and USGS are focusing on process control. Current prototypes are characteristic of lunar highlands material.

We plan to characterize and prototype mare types in the future.

Overview of lunar simulants

Simulant(s)	Type	Primary Reported Use	Manufacturer	feedstock	status
NU-LHT series	Highlands	General	NASA-MSFC and USGS	Stillwater mine (MT), commercial minerals	In production and use
OB-1	Highlands	Geotechnical	Norcat	Shawmere anorthosite, olivine slag glass	In production and use
JSC-1 (-1A, -1AF)	Mare, low-Ti	Geotechnical and lesser chemical	Orbitec, Inc.	Basalt ash, San Francisco volcanic field (AZ)	In production and use
FJS-1	Mare, low-Ti	Geotechnical	Japanese, (JAXA, LETO)	Mt. Fuji area basalt	No longer available
MLS-1	Mare, high-Ti	Chemical	University of Minnesota	Basalt sill, Duluth complex	No longer available

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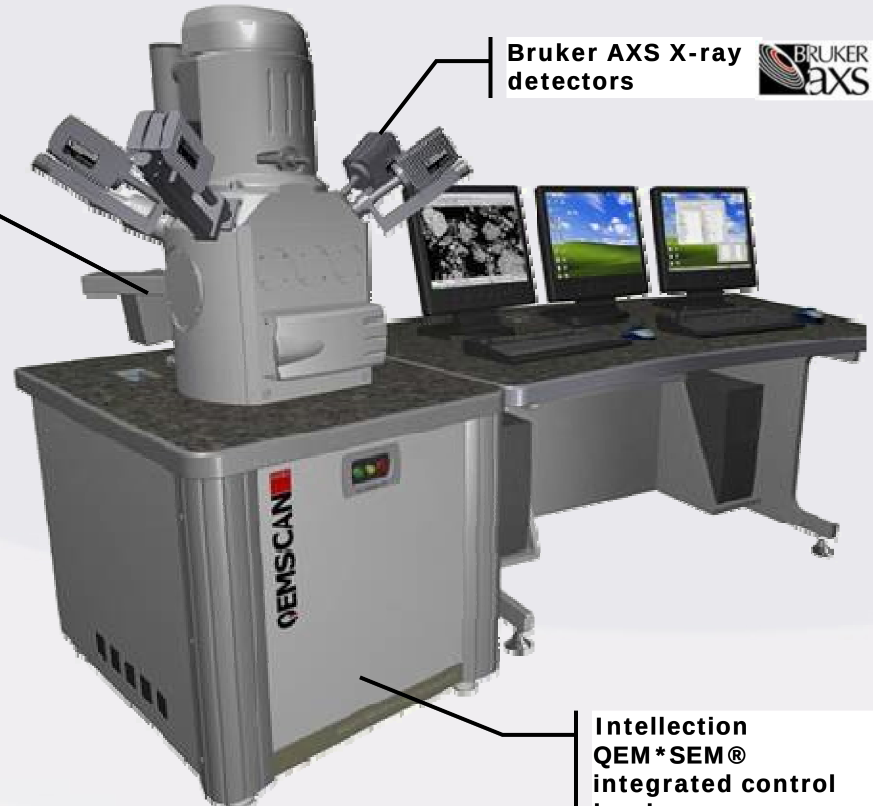
QEMSCAN® instrumentation

Carl Zeiss custom SEM



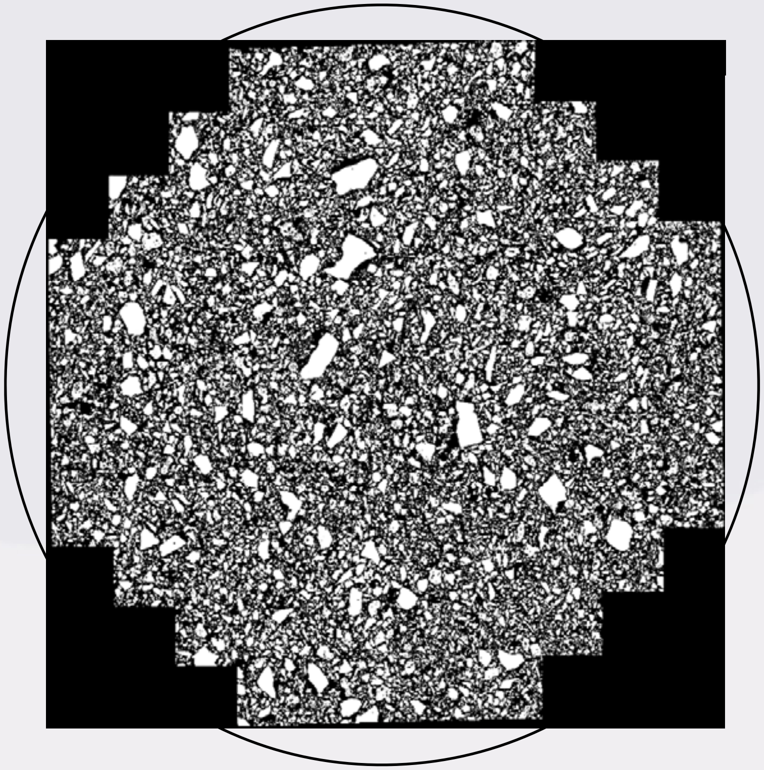
Bruker AXS X-ray detectors

Intellection QEM*SEM® integrated control hardware

QEMSCAN® uses advanced e-beam technology from Carl Zeiss and combines this with high resolution BSE and SE imaging, and state-of-the-art Energy Dispersive Spectrometers. It integrates these using iDiscover software to provide a solution capable of identifying most rock-forming minerals in just milliseconds

QEMSCAN® analysis

Digital photograph of polished block



QEMSCAN® Backscattered Electron photo-micrographic montage of a polished block

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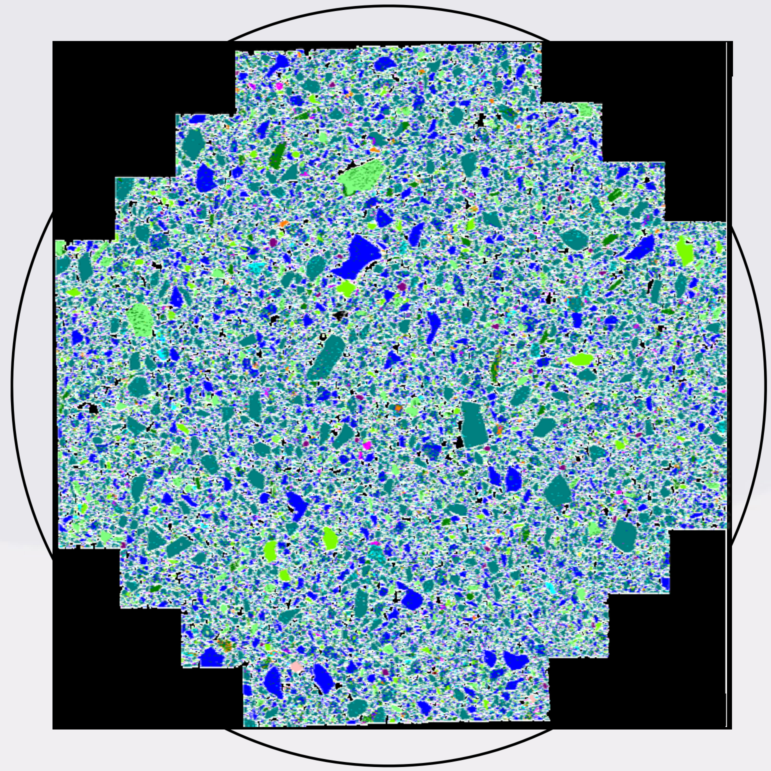
QEMSCAN® analysis

Digital photograph of a 30mm diameter polished block



QEMSCAN® false-coloured, digital particle mineral map montage of a polished block

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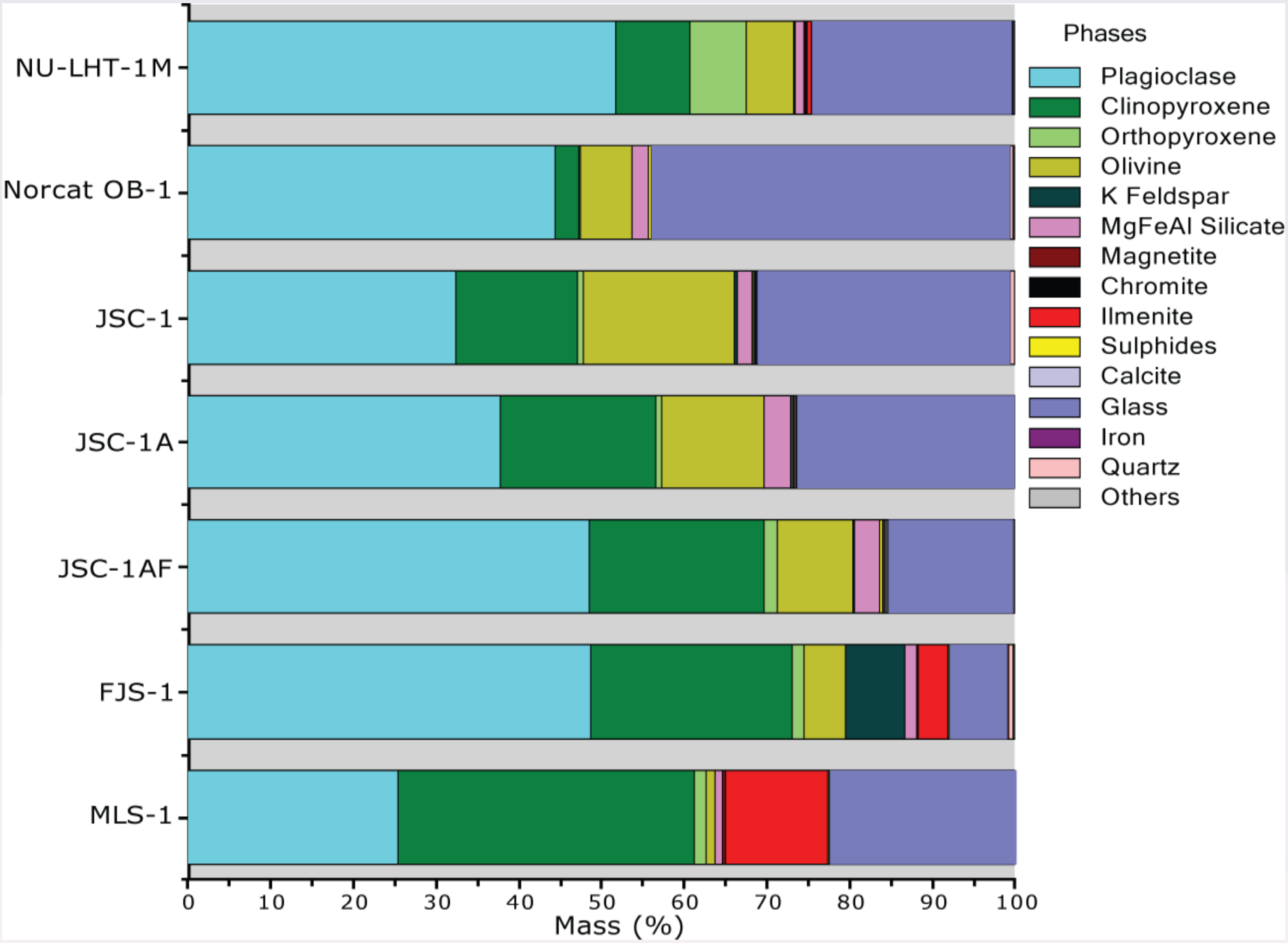
Results: QEMSCAN® modal analysis
Average of two replicate runs

These modal data are total % of phase proportion regardless of occurrence, e.g., as free minerals, in a lithic fragment or agglutinate...

Minerals	NU-LHT-1M	OB-1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Plagioclase	51.87	44.35	32.47	37.83	48.47	48.78	25.45
Clinopyroxene	8.95	2.95	14.67	18.77	21.15	24.39	35.86
Orthopyroxene	6.76	0.19	0.65	0.66	1.62	1.37	1.37
Olivine	5.79	6.27	18.29	12.44	9.22	4.94	1.06
Glass	24.07	43.22	30.86	26.67	15.68	7.15	22.29
Magnetite	0.15	0.07	0.02	0.01	0.00	0.04	0.45
Chromite	0.11	0.01	0.01	0.00	0.00	0.01	0.00
Ilmenite	0.53	0.00	0.07	0.11	0.08	3.65	12.38
Sulphides	0.02	0.35	0.19	0.17	0.31	0.16	0.10
Iron	0.20	0.01	0.00	0.00	0.00	0.00	0.06
MgFeAl Silicate	1.13	1.83	1.76	3.06	3.09	1.53	0.82
K Feldspar	0.13	0.08	0.39	0.07	0.11	7.24	0.07
Quartz	0.21	0.48	0.50	0.01	0.04	0.47	0.00
Calcite	0.06	0.08	0.07	0.11	0.14	0.00	0.02
Others	0.04	0.12	0.07	0.07	0.08	0.27	0.08
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Results: QEMSCAN® modal analysis
Average of two replicate runs



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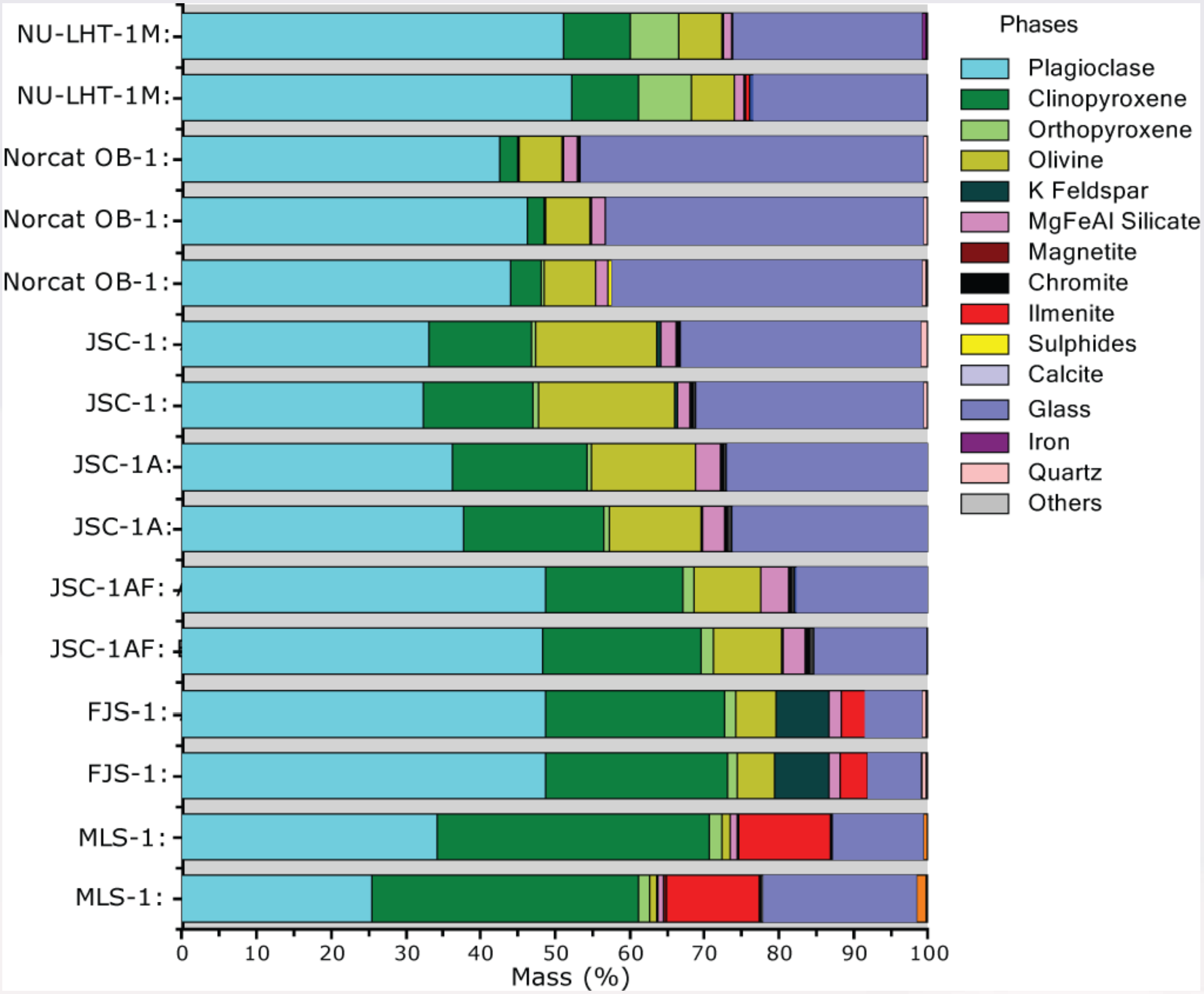
Results: QEMSCAN® modal analysis
Replicate runs



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Modal Analysis

Modal analysis measures the proportion by area% of a phase (mineral or glass) in a material. Area% is the same as volume% in a randomly oriented material and mass% can be computed if composition is known.

Physical characteristics such as hardness, fracture and cleavage behavior (which control abrasiveness, e.g.) are intrinsic characteristics of minerals and glass.

Geo-mechanical behavior of a material is controlled largely by the proportions of these constituent parts, as well as by the size and shape distributions of particles.

Modal proportions of phases are also the first piece of information necessary in understanding physiochemical behavior important to melting, oxygen extraction, etc.

Results: QEMSCAN® modal analysis

Average of two replicate runs

Minerals	Apollo 16: 64001/2	NU-LHT-1M	OB-1	Apollo 11 &12	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Plagioclase	43-44	51.87	44.35	11-15	32.47	37.83	48.47	48.78	25.45
Clinopyroxene	0.6-0.7	8.95	2.95		14.67	18.77	21.15	24.39	35.86
Orthopyroxene	~2.5	6.76	0.19		0.65	0.66	1.62	1.37	1.37
Total Pyroxene	~3	*15.71*	*3.14*	25-37	*15.32*	*19.43*	*22.77*	*25.76*	*37.23*
Olivine	0.8-0.9	5.79	6.27	2-10	18.29	12.44	9.22	4.94	1.06
Glass	44-46	24.07	43.22	31-45	30.86	26.67	15.68	7.15	22.29

Highlands data are from QEMSCAN® analysis of thin sections from 64001,6031 and 64002,6019 Apollo 16 drive core.

Mare data are from Taylor et al. (1996) from 10084,1618, 12030,122, and 12001,7 Apollo 11 and 12 samples of low-Ti mare samples of varying maturity. Values determined by SEM EDS

Other crucial phases

Minerals that occur in much less abundance such than those mentioned can be very important to ISRU processes.

Ilmenite ($FeTiO_3$) is an important lunar mineral for oxygen extraction by H_2-reduction.

Halogen (F, Cl)-bearing phases like apatite can have significant adverse effects on many ISRU processes. Sulfur, phosphorus, bromine and iodine bearing phases are also almost certain to be important.

Data on these minerals is still being refined.

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Chemical composition of minerals and glass

In addition to modal proportions, the chemical make-up of phases exerts a huge control over physiochemical processes such as melting and those processes necessary to oxygen extraction.

Plagioclase feldspar, a major constituent of lunar regolith, is a good example.

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Plagioclase chemistry

Another consideration is the chemical composition of the plagioclase mineral grains.

Plagioclase feldspar is a solid solution mineral that varies between two end-member compositions:

Anorthite - $CaAl_2Si_2O_8$

and

Albite - $NaAlSi_3O_8$

$\Longrightarrow$ The Ca/Na and Al/Si ratios vary simultaneously.

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Plagioclase composition

Lunar Highlands:	An >90%
NU-LHT-1M range:	An 75-85%
OB-1:	Shawmere, approx. An 75%?
Lunar Mare:	An 75-95%
JSC-1:	An 64-71% (Carpenter 2005)
JSC-1A:	An 70% (average -- Hill et al., 2007)
JSC-1AF:	An 70% (Carpenter, 2006)
MLS-1:	An 44-50% (Carpenter, 2005; Hill et al., 2007)

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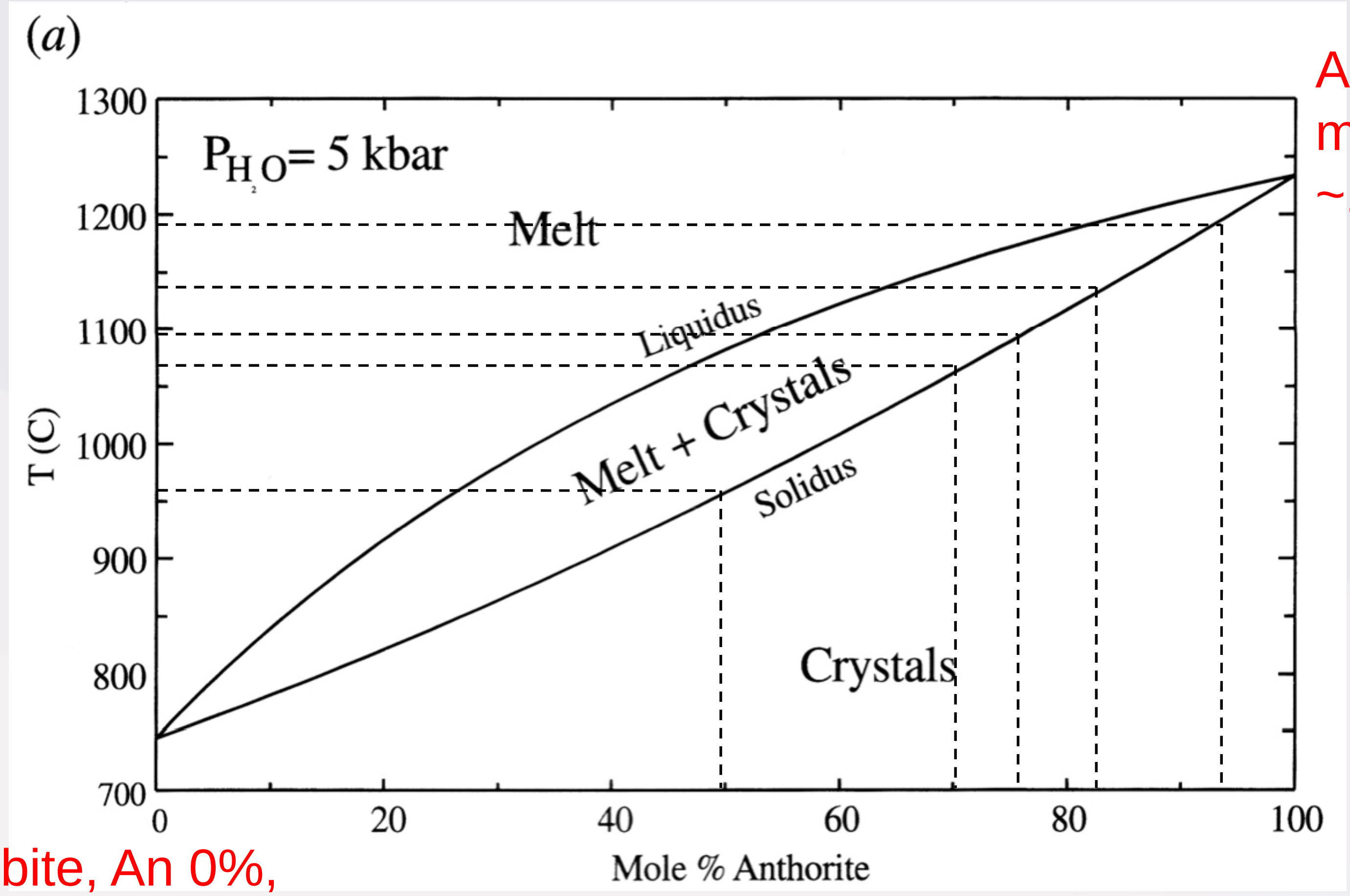
Example - Why mineral chemistry matters



An 100% melts at ~1230° C

Albite, An 0%, melts at ~750° C

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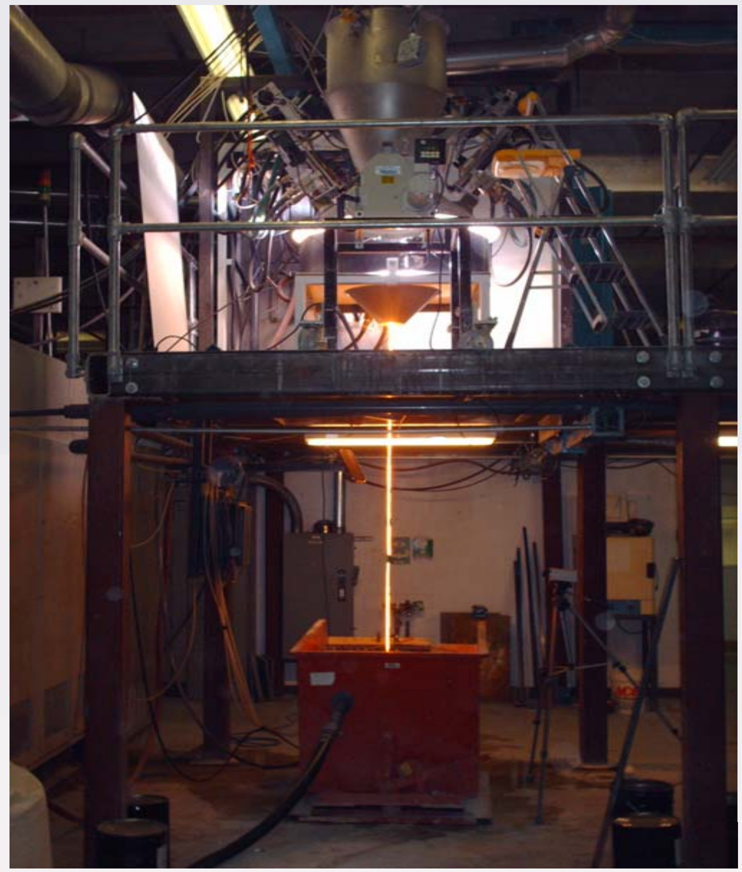
NU-LHT series glass: plasma melting

NU-LHT-1M and -2M: glass is derived from melting fine-grained material (mill sand) from the Stillwater mill.



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Glass in lunar simulants

NU-LHT-1M:	Glass is derived by plasma-melting of noritic feedstock Ca-Al-Si with moderate Fe and Mg
OB-1:	Glass is an olivine slag Fe and Mg-rich with Si
JSC-1 series:	Natural basalt glass Fe-Mg-Ca-Al-Si with lesser Na
FJS-1:	Natural basalt glass no analyses available
MLS-1:	Glass is derived by plasma-melting of basaltic feedstock Fe-Mg-Ca-Al-Si with lesser Na

Some simulant glass chemistry

oxide	NU-LHT	JSC-1A	JSC-1AF
SiO_2	46.6	46.8	46.11
TiO_2	0.115	2.44	2.8
Al_2O_3	21.55	13.9	14.92
FeO**	5.08	12.1	12.66
MnO	0.09	0.21	0.22
MgO	9.5	5.6	5.07
CaO	12.6	10.5	9.98
Na_2O	0.965	3.89	3.96
K_2O	0.12	1.17	1.43
P_2O_5	0.07	1.04	1.02
Cr_2O_3	0.12	b.d.l.	0.01
LOI	2.74	n.d.	n.d.
Total	99.55	97.65	98.18

**total Fe as FeO

NU-LHT values are from an analysis of the feedstock Stillwater "mill sand" melted to form glass.

JSC-1A and -1AF analyses from Hill et al. (2007) and Paul Carpenter (2005, 2006) reports and presentations.

Conclusions

We are compiling huge numbers of data points on lunar regolith and simulants. Analysis and refinement is continuing.

Modal composition is one important parameter to both geotechnical and to physiochemical behavior.

For physiochemical behavior important to many ISRU purposes, phase chemistry is also very important, perhaps particularly with regards to glass chemistry.

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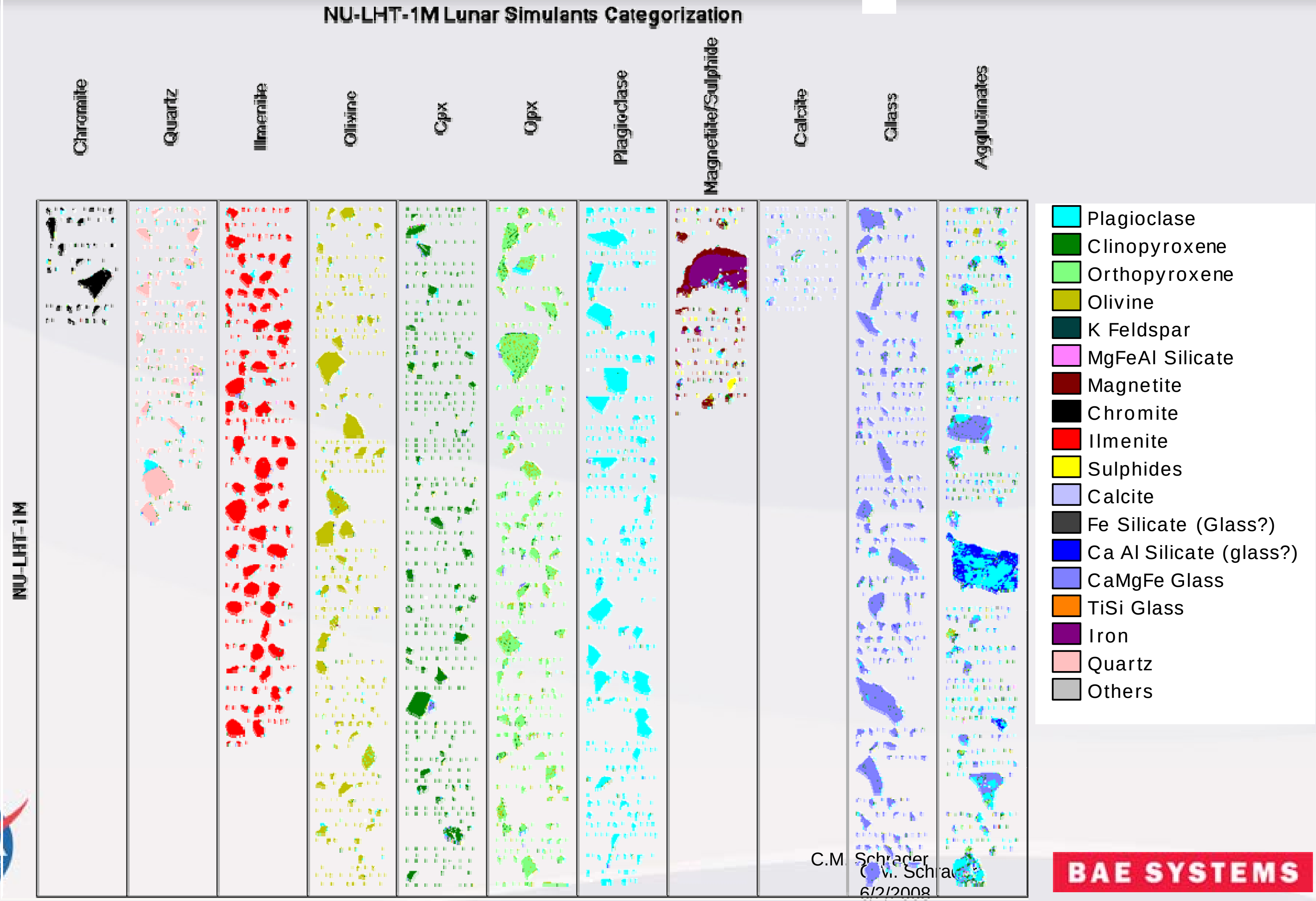
NU-LHT-1: QEMSCAN® particle analysis



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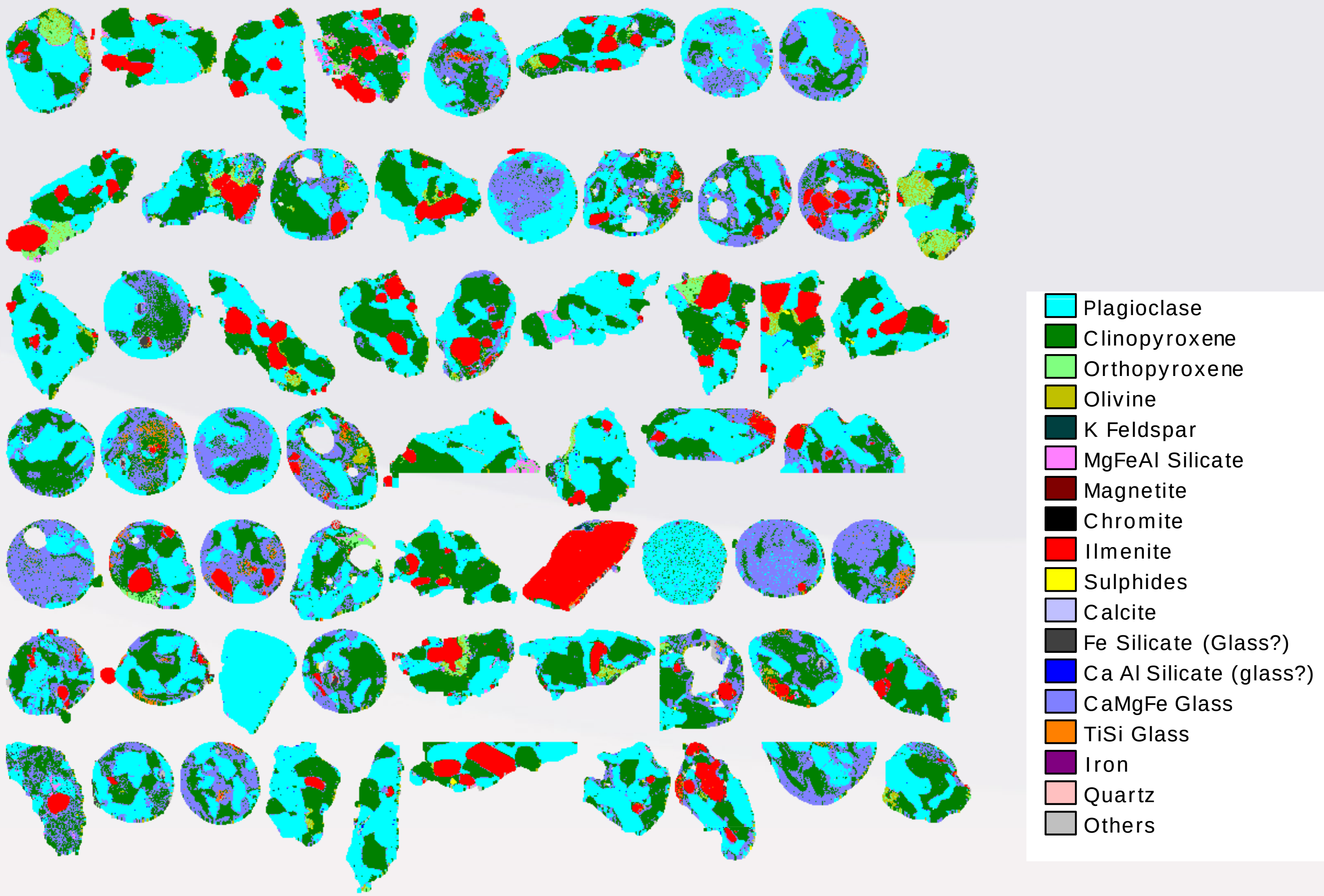
MLS-1: QEMSCAN® particle analysis



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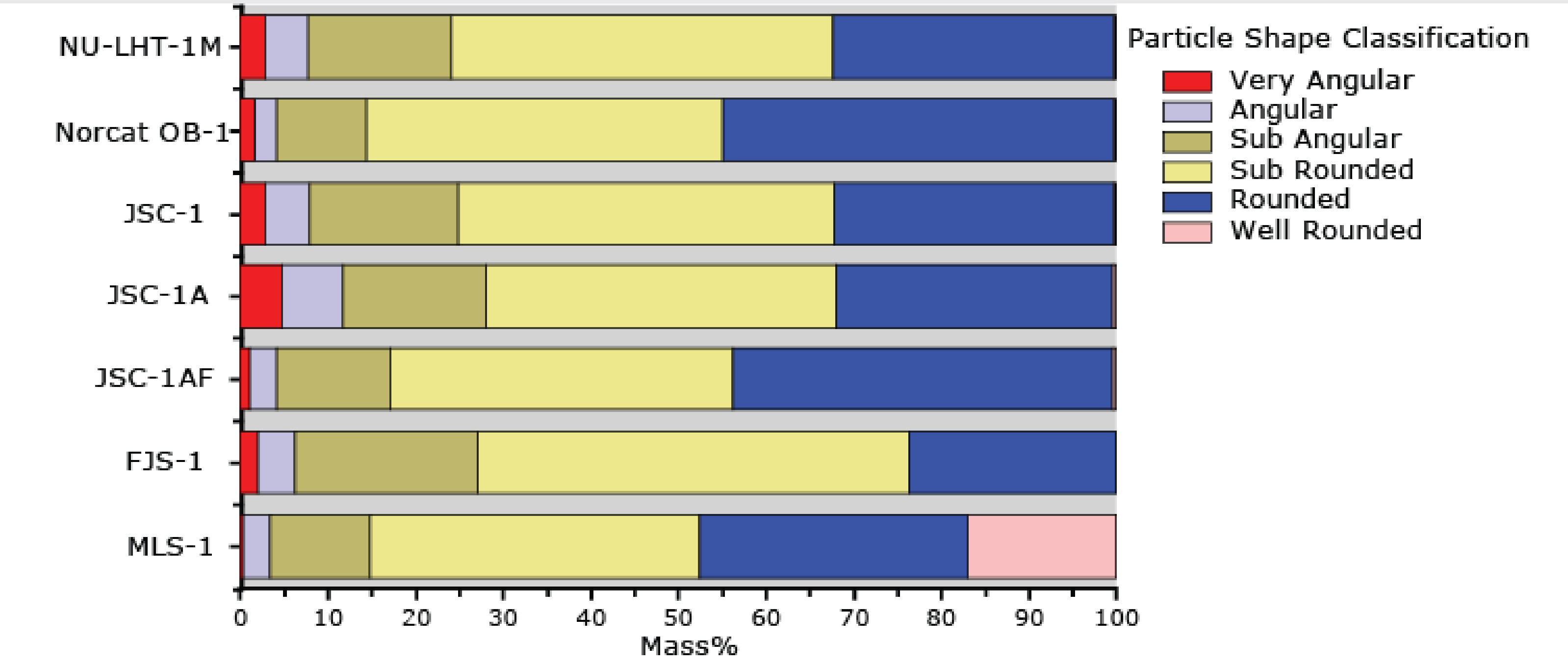
Results: QEMSCAN®determined particle shape



Particle Shape Classification	NU-LHT-1M	Norcat OB1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS1
Very Angular	2.85	1.74	2.86	4.72	1.11	1.99	0.37
Angular	4.90	2.35	5.13	7.02	3.06	4.19	3.04
Sub Angular	16.33	10.35	16.98	16.34	12.97	20.92	11.47
Sub Rounded	43.67	40.74	42.94	40.02	39.15	49.21	37.49
Rounded	32.05	44.55	31.95	31.59	43.42	23.61	30.77
Well Rounded	0.20	0.27	0.14	0.31	0.30	0.07	16.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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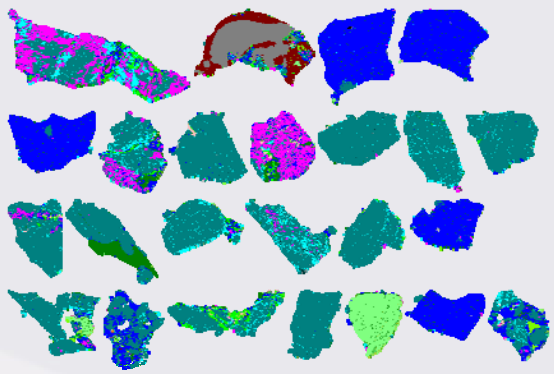
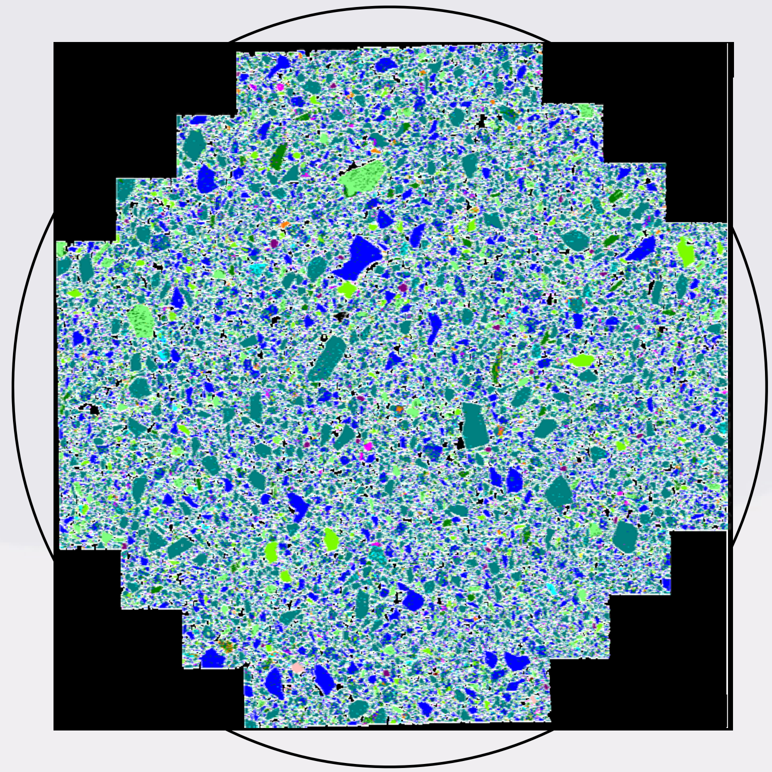
QEMSCAN® analysis



Example of particles delineated by image analysis.

Example of a mineral and phase list.

- Quartz
- Plagioclase (Ab-An60)
- Plagioclase (An60-An100)
- K Feldspar
- Clinopyroxene
- Orthopyroxene
- Olivine
- Mg Silicates
- Ca Al Silicate Glass
- MgFeAl Silicate
- CaMgFe Glass
- Iron
- Magnetite
- Chromite
- Ilmenite



Mosaic images are particulated using off-line image analysis software, so that each measured particle can be examined and quantified for parameters such as modal composition, texture and shape.

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